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1. Your reference	JWB/SS/57571
2. Patent application number *(The Patent Office will fill in this part)*	9906735.7
3. Full name, address and postcode of the or of each applicant *(underline all surnames)*	FET Applications Limited
Patents ADP number *(if you know it)*	7628621001
If the applicant is a corporate body, give the country/state of its incorporation	a British company
4. Title of the invention	Magnetoelastic Transducers
5. Name of your agent *(if you have one)*	Lloyd Wise, Tregear & Co.
"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	c/o Lloyd Wise, Tregear & Co., Commonwealth House, 1-19 New Oxford Street, London WC1A 1LW.
Patents ADP number *(if you know it)*	117001

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Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

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11. I/We request the grant of a patent on the basis of this application.

Signature Lloyd Wise, Tregear & Co. Date 23 March, 1999.

Lloyd Wise, Tregear & Co.

12. Name and daytime telephone number of person to contact in the United Kingdom

John W. Bluff (0171) 571-6200

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Title: Magnetoelastic Transducers

This application relates to a torque sensor based on a magnetised transducer element of magnetoelastic material, to a transducer element and to a method of forming such an element. The invention has particular utility to such transducer elements which are magnetised in a circumferential direction about an axis, particularly the axis of a shaft the torque in which is to be measured.

Transducers of this type are disclosed in related U.S. patents 5,351,555 and 5,465,627 (Garshelis, assigned to Magnetoelastic Devices, Inc.) and in U.S. patent 5,520,059 (Garshelis, assigned to Magnetoelastic Devices, Inc.). These patents describe torque sensing arrangements for a rotating shaft in which a transducer ring or torus is secured to the shaft to rotate therewith and to have the torque developed in the shaft transmitted into the transducer ring. The ring is of a magnetoelastic material circumferentially magnetised and the flux emanating from the ring due to the stress of the ring under torque is detected by a non-contacting sensor system as a measure of the torque.

Another proposal is described in British patent application 9808792.7 filed 23rd April, 1998 and a corresponding PCT application PCT/GB filed 11th March, 1999, published under the number WO on (Lloyd Wise, Tregear case 43832).

In this proposal a shaft of a material capable of exhibiting magnetoelastic material has a portion of it directly magnetised to support a circumferential magnetic field about the shaft axis, an approach which is contrary to the thinking in the prior art. The magnetised portion

of the shaft acts directly as the torque transducer element.

To illustrate the operation of a magnetoelastic torque transducer as represented by the above two proposals reference may be made to Figs. 1A and 1B which show a separate ring transducer element secured to a shaft and a transducer element provided by a portion of the shaft itself. The shafts rotate about the longitudinal axis A-A.

In Fig. 1a the shaft 10, assumed to be of circular cross-section, has the transducer ring 12 securely clamped on it by any of the means described in the three U.S. patents mentioned above. The transducer ring 12 supports a circumferential field M_c extending around the ring. If the shaft 10 is of low magnetic permeability, e.g. paramagnetic, the ring 12 is mounted directly on the outer surface of the shaft. If shaft 10 is ferromagnetic, that is of high permeability, a low permeability spacer (not shown) is mounted between the ring and the shaft.

In Fig. 1b, the solid circular shaft 10′ is of a magnetoelastic material having an integral portion 12′ of it directly circumferentially magnetised to provide the transducer element (the lines delineating portion 12′ are notional for clarity of illustration). As employed in previous torque sensors, with the shaft 10 or 10′ static and no torque applied, the circumferential field M_c is entirely contained within the transducer element 12 or 12′ so that an exterior non-contacting magnetic field sensor will not detect any field emanating from the transducer element. The application of a torque causes the contained

field to skew and the opposite sides of the transducer to be oppositely magnetically polarised (i.e. N-S) to generate a torque-dependent magnetic flux that links the poles externally of the transducer element to enable a magnetic sensor to detect the torque-dependent external field M_e. It will be understood that this external field forms a torus or doughnut around the shaft. Many different types of magnetic field sensor devices are available and many sensor arrangement configurations of field sensitive devices may be employed. In the instance illustrated in Fig. 1b, the transducer element 12′ is preferably axially bounded by circumferentially-magnetised guard regions 14a and 14b, one to each side. These provide respective poles at the interface that are of opposite polarity, i.e. have a repulsive effect, to the poles of the transducer element enhancing the emanation of externally detectable magnetic field from the transducer element for measurement of torque. The circumferential fields are induced to extend as deeply into the shaft 10′ as possible.

Another proposal to enhance the emanation of magnetic flux from the transducer element is to provide the transducer element portion 12" shaft 10" with an integral annular section 16 of raised profile as shown in Fig. 1C, so that the upstanding sides assist in emanating magnetic flux in an external loop. In contrast to the separate ring 12 of Fig. 1 in which all the field is confined in the ring, the annular section 16 is integral and homogeneous with the underlying shaft in Fig. 1c and the circumferential field extends into the body of the shaft.

This technique and that of using guard regions is discussed more fully in the aforementioned PCT application (Lloyd Wise, Tregear Case 43832). For the purpose of description of the principles underlying the present invention, no account will be taken of the guard regions where they are used.

Referring to Figs. 2a and 2b, when the transducer element - 12′ is shown as an example, it is equally applicable to separate ring 12 - is subject to torque, a magnetic field M_e emanates from the transducer for sensing by a sensor arrangement 18 of any desired kind. The external field has a magnitude proportional to the torque and a polarity dependent on the direction of torque T (CW or CCW) as indicated in Figs. 2a and 2B respectively.

The problem posed to some users of magnetoelastic torque transducer elements of the circumferential magnetic field kind discussed above is that at zero torque in the shaft, the magnetic field output from the transducer element is zero. Outputs at or around the zero region are liable to be masked by noise. The present invention enables the provision of a real measurable output at zero torque with a range of linear measurement of magnetic field output against applied torque. The solution proposed by the present invention is to induce the circumferential field in the transducer element when the element is subject to a torque, a concept that will be referred to as pre-torquing. This is in contrast to prior proposals in which the establishing of the circumferential field in the transducer element is done without torque in the element.

This pre-torquing of the transducer element during magnetisation may be also called processing torque.

The invention and its practice will be further described with reference to Figs. 3 to 7 of the accompanying drawings in which:

Figs. 1a, 1b and 1c show examples of prior proposals for transducer elements magnetised to have a circumferential field,

Figs. 2a and 2b show an example of the emanated magnetic field for the transducer element of Fig. 1b subject to torques of opposite direction, i.e. clockwise (cw) and counter-clockwise (ccw);

Fig. 3 shows the circumferential magnetising of a transducer element under pre-torque and Fig. 3a shows the magnetising and pre-torque conditions as relating to a cross-section of the transducer element.

Fig. 4 shows a graph of magnetic field output (M_e) v. torque (T) for the circumferentially magnetised transducer element of Fig. 3 subject to a pre-torque.

Figs. 5a to 5d show response curves relating to different directions of pre-torquing and circumferential magnetisation;

Fig. 6 shows a sensor arrangement employing two transducer elements subjected to pre-torquing, Figs. 6a-6d graphically illustrating different responses obtainable with the two elements according to the direction of pre-torque and circumferential magnetisation respectively applied to the elements;

Fig. 7 illustrates one magnetising arrangement for

obtaining circumferential magnetisation; and

Fig. 8 is a block diagram of a sensor and processing circuit providing automatic gain control.

Referring to Fig. 3, a solid shaft 20 of the kind shown in Fig. 1b is seen being subject to magnetisation M_c at a portion 22 while under a predetermined torque T_0. The magnetising method may use a permanent magnet 24 brought up adjacent to the portion 22 of shaft 20 while it is rotating under the predetermined torque T_0. A preferred arrangement is shown in Fig. 7. Instead of a permanent magnet, an electromagnet may be used or the shaft subjected to an axially directed current. Various methods are available and some of these are disclosed in the above three U.S. patents and particularly U.S. patent 5,520,059; and also in above-mentioned PCT application (Lloyd Wise, Tregear Case 43832). Alternatively the shaft may be held static with the predetermined torque T_o applied to it while a magnet system is moved around it. Magnetisation by an axially directed current is also applicable to the static case.

Fig. 3a indicates the directions of pre-torque T_o and circumferential magnetisation M_c about the axis. The example shown has both of them clockwise. From Fig. 3a, it will be appreciated that their are four magnetising and pre-torque conditions - T_o is CW with M_c being CW or CCW; and T_o is CCW with M being CW or CCW. These enable different torque response curves to be established as will now be described.

When the circumferential field M_c is induced in the presence of torque T_o, this sets up the condition at which

zero external field is produced by the transducer element. When the pre-torque is relaxed so that the shaft returns to a zero torque state, the circumferential field is skewed to a certain extent resulting in its opposite sides becoming polarised as shown in Figs. 2a and 2b resulting in there being is a quiescent external field M_o at zero torque.

Fig. 4 illustrates the magnetic field output M_e available to an external sensor as a measure of torque T for a given direction, say CW, of magnetisation. The dashed line in Fig. 4 shows the conventional case without any processing torque or pre-torque during magnetisation. The torque axis of Fig. 4 shows the output field reversing as the torque passes through zero, e.g. as the torque goes from one direction (CW) to the other (CCW). At zero torque in the conventional case the circumferential field is trapped within the transducer element and there is no external magnetic field available for sensing.

The full line A in Fig. 4 shows the effect of pre-torquing as now proposed. The zero field output is at the pre-torque value, i.e. at a know predetermined torque,here shown as -To from a CCW pre-torque, providing a working range of torque extending from a negative value to a positive value in which the output field M_e is of the same polarity so that there is no signal polarity reversal to cope with in the processing circuitry, and with a real, non-zero, field output M_0 at zero torque lying with a useful range of torque response. It is to be noted that the absolute axial direction of the external flux emanated for a given direction of circumferential magnetisation differs

for different materials.

Fig. 4 shows one of the possible four combinations of circumferential field direction and pre-torque direction mentioned above. Figs. 5a to 5d illustrates graphically the responses due to these four possibilities in a given shaft with clockwise and counter-clockwise directions being defined as in Fig. 3. Figs. 5a to 5d show a set of line curves of the four responses of detectable output field (M_e) v. torque (T) and which may be summarised according to the following table labelled a)-d) in conformity with Figs. 5a-d.

Pre-Torque (T_o) Direction	Magnetising Field Direction	Output Field (M) (Zero Torque)	Response Slope
a) CW	CW	$-M_o$	+ve
b) CW	CCW	$+M_o$	-ve
c) CCW	CW	$+M_o$	+ve
d) CCW	CCW	$-M_o$	-ve

It is to be understood that for different materials, the sign of M_o and the slope may be reversed. However, the outcome is still four responses of the kind shown. These may be combined for plural transducer elements as will now be described. It will also be appreciated that any response can effectively be inverted by the processing of the electrical signals obtained from the magnetic field sensor.

It will be appreciated that the requirements for measurement of torques in shafts depend on the circumstances in which the shaft is used. For example, it

may always rotate in a single direction or it may be required to rotate bi-directionally. Torque sensors may also be applied in circumstances where one end of the shaft is fixed and the other end is subject to some applied torque to be measured.

It is an important facet of the present proposals to apply the pre-torquing concept to obtain advantageous results from shafts having multiple axially displaced transducer elements. Fig. 6 shows a shaft 30 having two transducer elements 32 and 34 axially spaced along the shaft but subject to the same torque in the shaft. It will now be explained how an advantageous torque transducer response can be achieved by using two transducer elements with various combinations of pre-torque and circumferential magnetisation directions. Each transducer element has its output field sensed by a respective sensor arrangement 36 and 38 connected to processing circuitry 40.

One form of magnetic field sensor arrangement, using saturable inductor sensing elements, and signal conditioning circuitry for generating the output indication signal is that disclosed in published PCT application PCT/GB98/01357, publication number WO98/52063.

Fig. 6a shows output responses, M v T, for the two transducer elements 32, 34 being magnetised and pre-torqued in accordance with conditions 5c) and 5b - opposite polarity circumferential fields of equal strength and equal but opposite pre-torques. There will always be an output from one transducer element even when the other is in the zero output region. This avoids having to make use of a

single low output signal whose signal-to-noise ratio (SNR) may be poor. Fig. 6b) shows output responses, M v T, for the two transducer elements being circumferentially magnetised with the same polarity and of equal strength but with equal but opposite pre-torques - Figs 5b) and 5a). These outputs may be combined (summed) at 40 to give a resultant (dashed line) extending through the zero origin but with the advantage that the measurements at or near zero torque will have been made with signals of good SNR.

Figs. 6c and 6d are similar to the conditions of Figs. 6a and 6b but relate to cases where the circumferential fields in transducers 32 and 34 are of different strengths. Still more variations are readily visualized by using different magnitudes of pre-torque. The transducer elements whether they are of the kind integral with the shaft or of the separately attachable ring type have response characteristics established by any of the parameters: direction of pre-torque and its magnitude, and direction of circumferential magnetisation and its strength.

Another important use of these multiple field arrangements as the basis of an automatic gain control or calibration for a torque sensor system. Take, for example, the situation of Fig. 6a. It will be understood that if the two output signals are summed, the sum should be a constant value (M_s = 2Mo) at all torques. Over time the circumferential fields may weaken so that if an initial sum value M_i is stored as a calibration point, the later obtained instantaneous sum M_s can be compared with M_c and

used to derive a compensating value to correct later sensor measurements.

This compensation procedure can be applied where the two fields are not equal in strength but more computation will be required.

In order to better explain the application of automatic gain control or compensation, reference is made to Fig. 8 which shows a block diagram of a sensor and signal processing circuit for an arrangement broadly in accord with Fig. 6 to implement a measurement response of the kind illustrated in Fig. 6b using the inversion of one sensor signal to obtain a reference value such as indicated by M_8 in Fig. 6a. The example to be illustrated has transducer regions 32 and 34 magnetised in accord with the responses of Figs. 5c and 5a respectively, namely, opposite but equal magnitude pre-torques and the same circumferential field direction, and of equal strength.

Referring to Fig. 8, it shows an analogue processing circuit 40 for processing the signals from sensors 36 and 38 of Fig. 6. The sensors 36 and 38 are illustrated as single coil sensors 60 and 62 respectively with which is included a respective driver and control circuit and respective buffer amplifiers 64 and 66. The manner in which coil-type magnetic field sensors are employed in transducer systems and a specific circuit for this purpose are disclosed in PCT application GB98/01357 published under the number WO98/52063. Each of the buffer amplifiers 64 and 66 has associated with it a means for adjusting the amplifier gain, assumed to be nominally unity, and the

amplifier offset. The sensors 60 and 62 have respective voltages V_1 and V_2 induced in them. The sensors are mounted to have the voltages V_1 and V_2 induced in the same sense and to have any signal due to the earth's magnetic field or other extraneous field induced in the same sense. Thus each of V_1 and V_2 is in practice the resultant of the torque dependent magnetic flux sensed thereby and any extraneous unwanted flux.

In one of the sensors, 38, the input signal is inverted so that the buffer amplifiers produce output signals V_1 and $-V_2$ for further processing. The response curves at this point are now equivalent to Fig. 6a. The circuit 40 comprises a main signal path 70 and an automatic gain control loop 80. The circuit is designed to combine the signals V_1 and V_2 to provide an output voltage V_o following the torque-dependent dash line curve in Fig. 6b, i.e. $V_o = V_1 - V_2$ in the ideal case. It will be noted from Fig. 6b that V_1 and V_2 are of equal magnitude, follow torque curves of equal slope, one increasing linearly with torque T from the zero torque point and the other decreasing linearly with torque T from that point.

In the main signal path 70, the voltages V_1 and $-V_2$ are applied to inputs of respective summing amplifiers 72 and 74 of equal (unity) gain. Each amplifier has a second input receiving a signal whose derivation is described below. The output of amplifiers 72 and 74 are applied as inputs to an output summing amplifier 76 to provide the output V_o. Amplifier 76 is a gain controlled amplifier having an input 78 for receiving a gain control signal from

the gain control path 80.

The automatic gain control (AGC) loop includes a difference amplifier 82 to which the voltages V_1 and $-V_2$ are applied to thereby obtain a reference signal which is a sum signal ($V_1 + V_2$) providing, in the ideal case, a constant value signal across the torque range equivalent to M_s in Fig. 6a. This sum signal is applied through block 84 to develop a signal at appropriate level to control the gain of summing amplifier 76 in accord with an initialising procedure discussed further below. The action of this forward gain control loop is further described below.

The output of difference amplifier is divided-by-2 at 86 and the output is passed directly to a second input of amplifier 72 and via an inverter 88 to a second input of amplifier 74 to re-enter the main signal path.

The operation of the circuit 40 is as follows.

The signals applied to the two inputs of amplifier 72 are V1 and a signal derived from the summation of V_1 and V_2 in the AGC loop 80. The signals applied to the two inputs of amplifier 74 are $-V_2$ and the same second signal as applied to amplifier 72, but inverted. The signals applied to the inputs of amplifier 76 from amplifiers 72 and 74 are summed subject to a gain control to provide an output

$$V_o = k\ (V_1 - V_2).$$

It is worth noting here that the sensor devices 60 and 62 were so arranged that any induced signal components, such as from the earth's magnetic field were in the same sense with respect to V_1 and V_2 so that these components

will be cancelled from the final output.

The sensor circuits 36, 38 and the processing circuit 40 are initially set up so that the output V_o represents the desired dashed line response of Fig. 6b by combining the V_1 and V_2 responses as a function of torque, e.g. the responses 32 and 34 of Fig. 6b.

It will be understood that the compensation techniques discussed above could be implemented in software. For example, the sensor output signals V_1 and V_2 may be digitised and the functions of the signal processing circuit 40 implemented on the digitised signals using software routines.

One of the potential problems with circumferential magnetic fields, such as 32 and 34, is that they may weaken over time. Thus for the same torque values, lesser values of V_1 and V_2 will be obtained. The initialising procedure may make use of the magnetisation established under the pre-torque values (Fig. 6b). The sum of V_1 and V_2 at the sensor buffer output can be identified with a specific torque value - $2T_o$-in this example and thus with a torque measurement sensitivity (volts/Nm). The offset and gain (slope) resistors R1 and R2 associated with the sensor buffer amplifiers provide a means of ensuring that the sum ($V_1 + V_2$) to be used as a reference is constant across the range of torque measurement. Later changes in the summation ($V_1 + V_2$), such as weakening of the transducer region fields, is then compensated by adjusting the gain of amplifier 76 (i.e. the factor "k") by means of the AGC loop 80. This sets the gain or scaling factor of the amplifier

76. The loop can also act to compensate perturbations in the V_1 and V_2 signals during, for example, rotation of a shaft whose torque is being measured. This compensation can be afforded on a real-time basis as the shaft is rotating.

The system can compensate for the effect of temperature changes on the basic sensor sensitivity. It can compensate for changes in the distance between the magnetic field sensor and the shaft as the shaft rotates. Generally, aging effects, e.g. leaching away of the transducer region fields will be compensated to maintain the initial torque sensitivity.

Reverting to the magnetising arrangement indicated at 24 in Fig. 3, a more preferred arrangement is seen in Fig. 7 which shows a cross-section through the portion 22 to be magnetised. A pair 50 of opposite polarity magnets have respective ends 52, 54 adjacent the shaft but a little spaced to generate a field between them having an essentially circumferential direction and through which the circumference of the shaft is rotated.

Claims

1. A transducer element of magnetoelastic material for a torque sensor having a closed loop of magnetisation within the material, characterised in that the transducer element emanates a magnetic field that is a function of torque over a range of torque values that includes a non-zero value at zero torque.

2. A transducer element as claimed in Claim 1 which is of the annular ring kind attachable to a shaft and circumferentially magnetised.

3. A transducer element as claimed in Claim 1 which is a circumferentially magnetised integral portion of a shaft.

4. A method of forming a transducer element as claimed in Claim 1, 2 or 3 wherein the element is subject to a predetermined torque while establishing said closed loop of magnetisation therein.

5. A method of forming a transducer element in a shaft subjectable to torque about a predetermined axis, in which a predetermined torque about said axis is established in a portion of the shaft and said portion is given a circumferential magnetisation while subject to the predetermined torque.

6. A method of forming a transducer element in a shaft as claimed in Claim 5 in which another or the same predetermined torque is established in another portion of said shaft and said other portion is given a circumferential magnetisation while subject to the other or the same predetermined torque.

7. A method as claimed in Claim 6 in which a selection is

made for the direction of circumferential magnetisation and the direction of the associated predetermined torque for each of the shaft portions to provide two transducer elements having different response characteristics of magnetic field output as a function of torque.

8. A shaft assembly having two axially-displaced transducer elements subject to torque applied about an axis of the shaft, each transducer element being of the magnetoelastic kind having a circumferential magnetisation about said axis of the shaft, wherein each transducer element provides a magnetic field output versus torque response that has a non-zero value at zero torque.

9. A shaft assembly as claimed in Claim 8 in which each transducer element has a zero magnetic field output at a respective predetermined torque.

10. A shaft assembly as claimed in Claim 9 in which each transducer element comprises an integral portion of the shaft.

11. A shaft assembly as claimed in Claim 9 in which each transducer element comprises a ring secured to the shaft.

12. A torque sensor system for a shaft or the like subject to torque about a predetermined axis comprising a transducer element as claimed in Claim 1 or 2, and a magnetic field sensor arrangement for detecting the torque-dependent field emanated by the transducer element.

13. A torque sensor system for a shaft subject to torque about a predetermined axis comprising a transducer element as claimed in Claim 3 whose shaft is the aforesaid shaft, and a magnetic field sensor arrangement for detecting the

torque-dependent field emanated by the transducer element.

14. A torque sensor system comprising a shaft assembly as claimed in Claim 8, 9, 10 or 11 and a respective magnetic field sensor arrangement responsive to the magnetic field emanated by each transducer element to provide a torque-dependent output signal, and means for combining the torque-dependent signals to provide an output signal therefrom.

15. A torque sensor system comprising a shaft assembly as claimed in Claim 8, 9, 10 or 11 and a respective magnetic field sensor arrangement responsive to the magnetic field emanated by each transducer element to provide a torque-dependent output signal, and signal processing means which comprises a first channel responsive to at least one of the torque-dependent signals, said first channel comprising an output means having a controllable gain for producing an output signal representing a measure of torque, and which also comprises a second channel comprising means for combining the two torque-dependent output signals to provide a reference signal and means response to said reference signal to apply a control signal to said output means to control the gain thereof.

16. A torque sensor system as claimed in Claim 15 in which said first channel is operable to provide an output signal by combining the torque-dependent output signals relating to the two transducer elements.

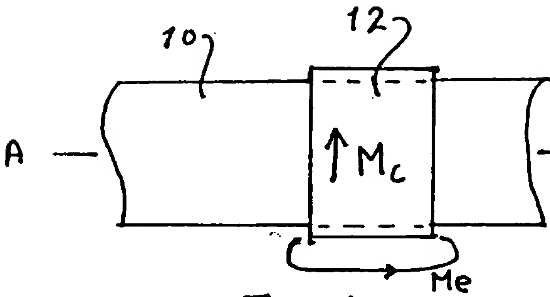


Fig. 1a

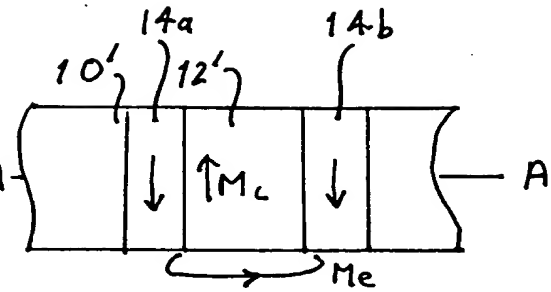
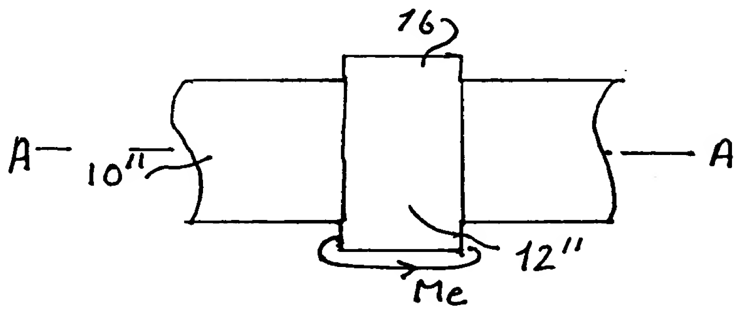


Fig. 1b

Fig. 1c



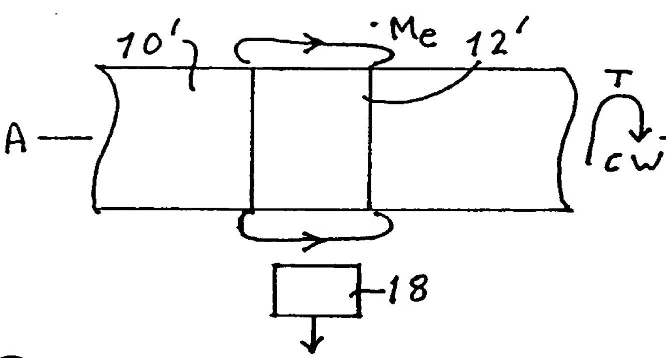


Fig. 2a

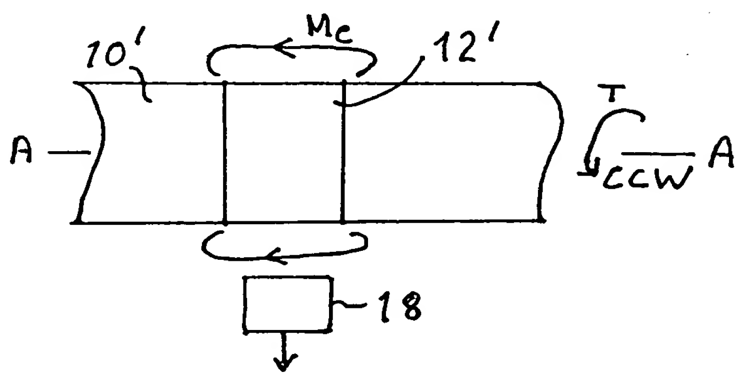


Fig. 2b

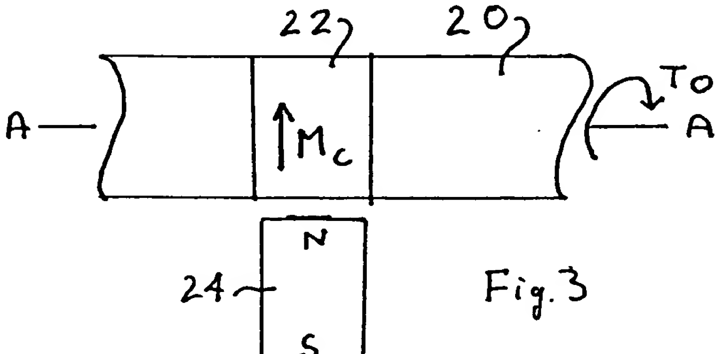


Fig. 3

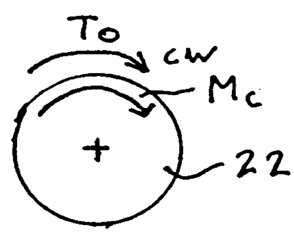


Fig. 3a

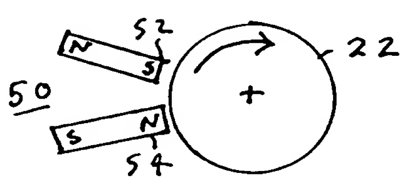


Fig. 7

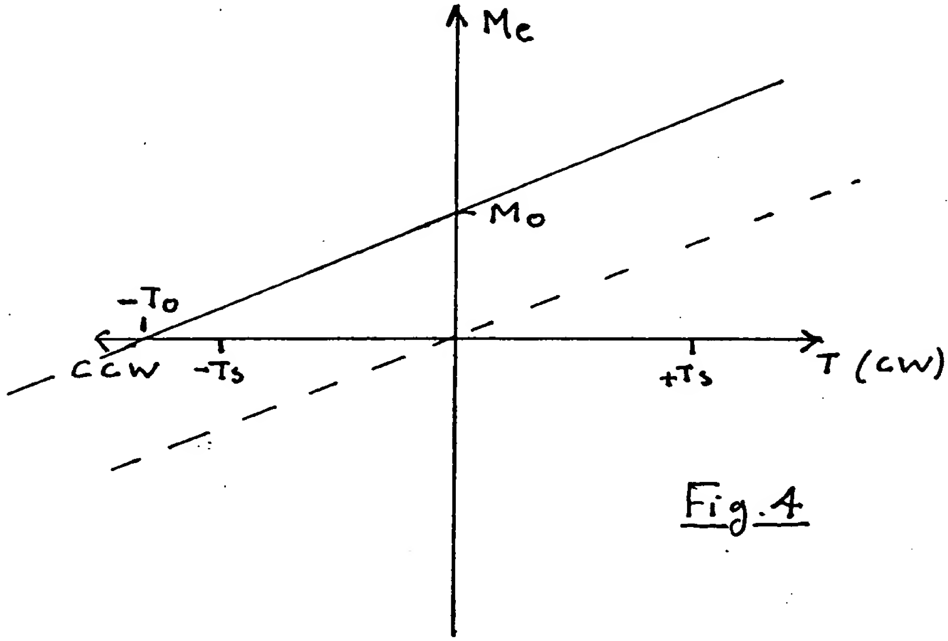


Fig. 4

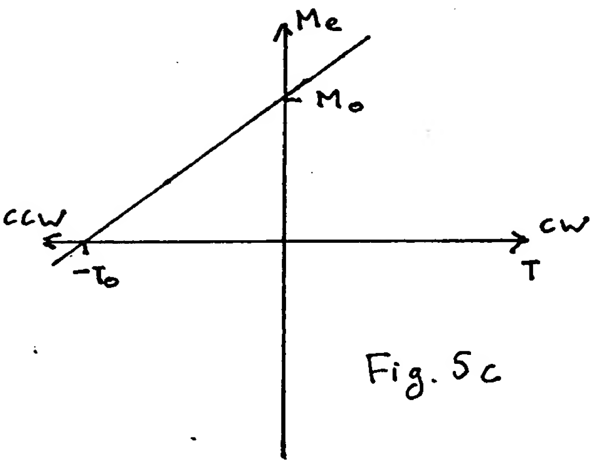


Fig. 5c

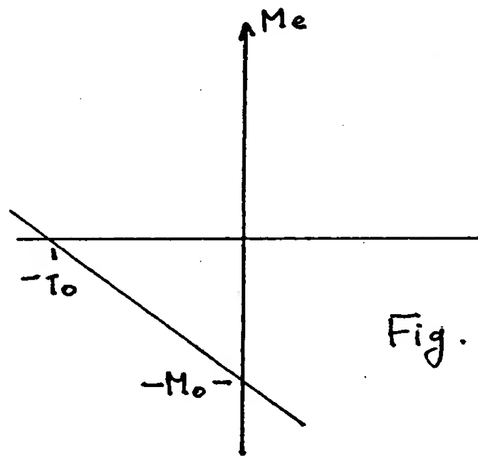


Fig. 5d

Fig. 5

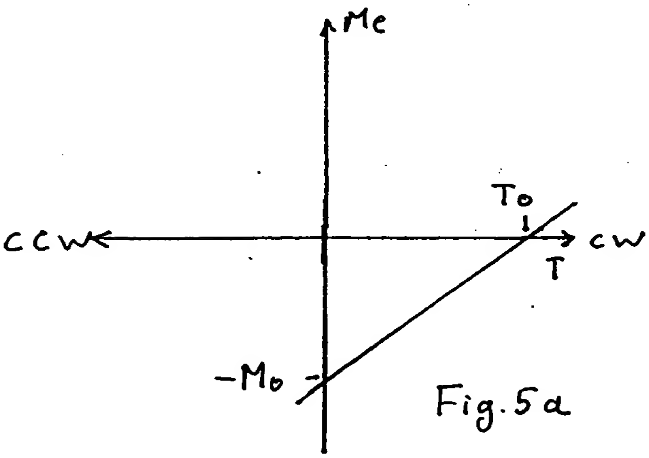


Fig. 5a

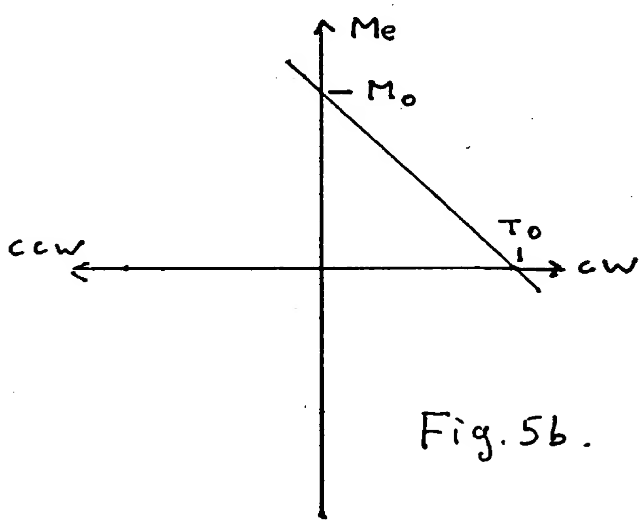


Fig. 5b.

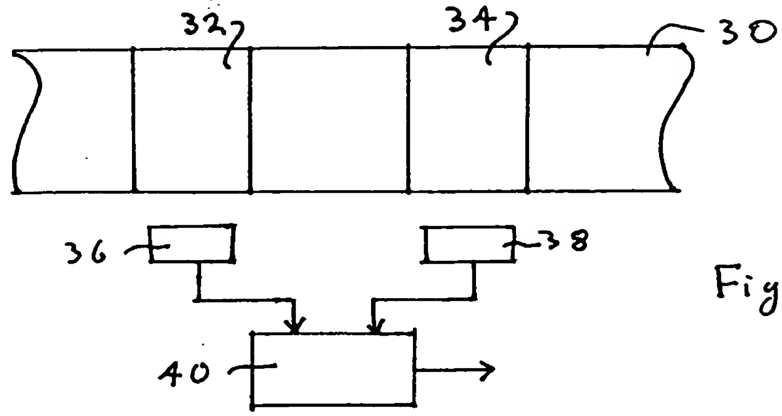


Fig. 6

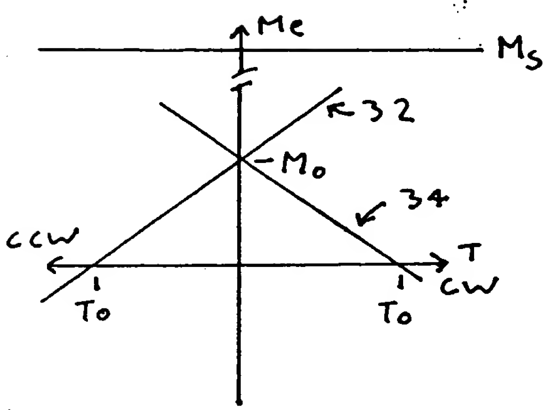


Fig. 6a

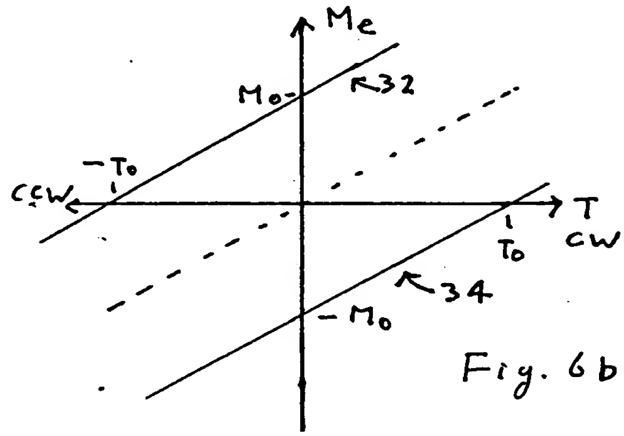


Fig. 6b

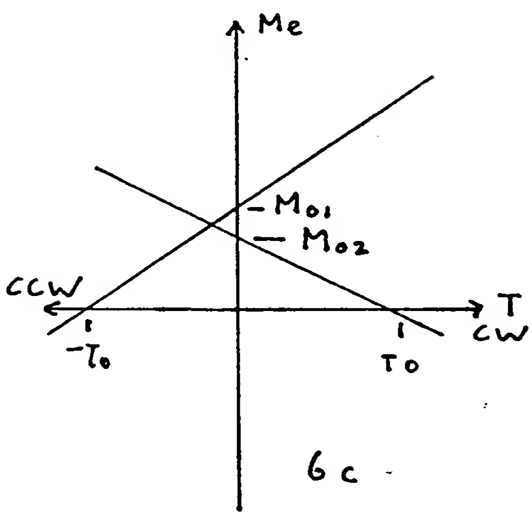


Fig 6c

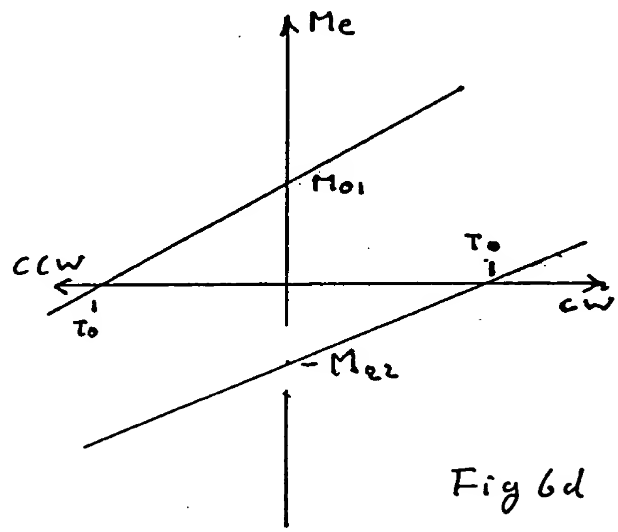


Fig 6d

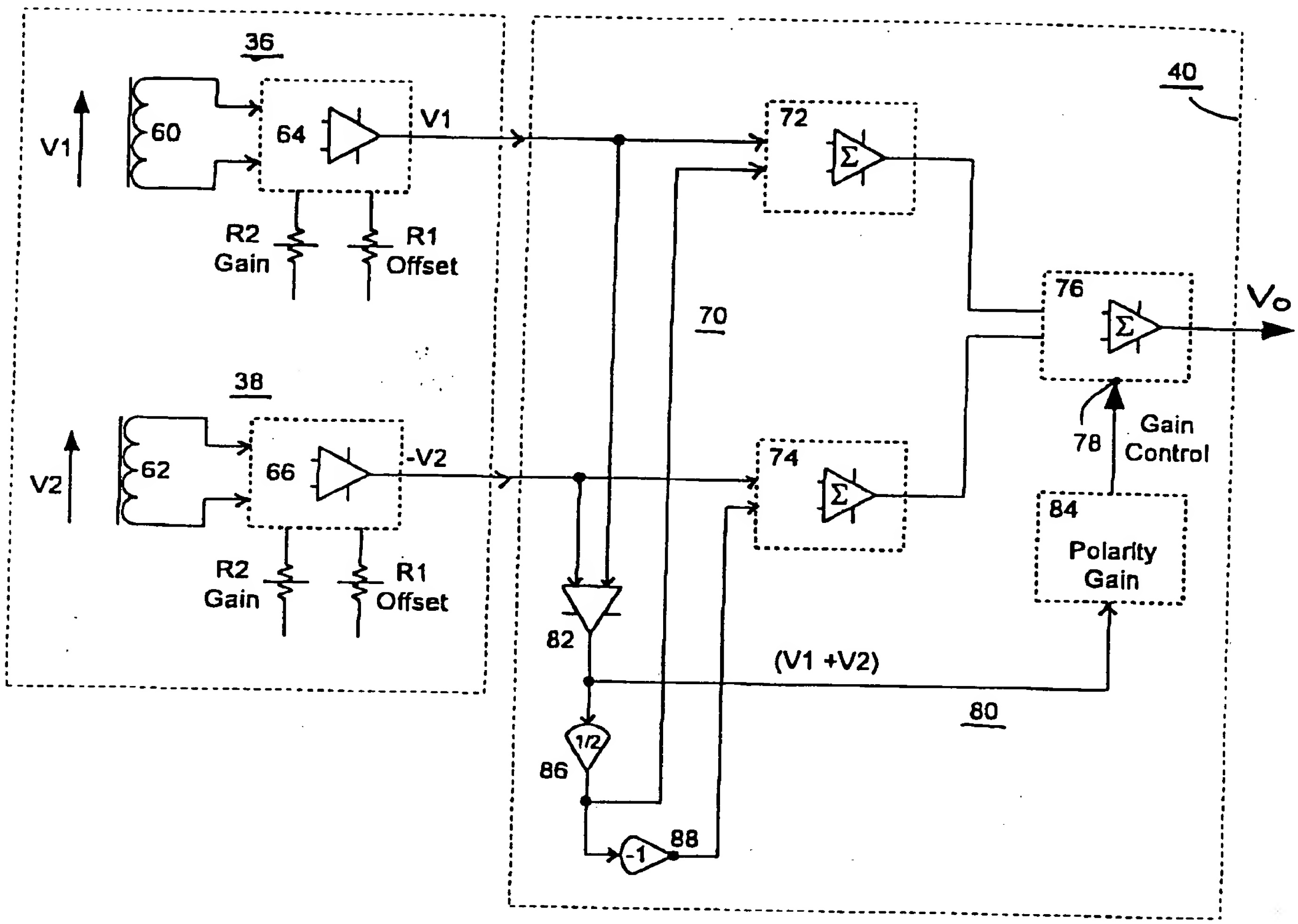

36
V1
60
64
V1
R2
Gain
R1
Offset
38
V2
62
66
-V2
R2
Gain
R1
Offset
40
72
70
74
76
Vo
78
Gain
Control
84
Polarity
Gain
82
(V1 +V2)
80
1/2
86
-1
88

Fig. 8